Technical Note

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

A SEISMIC DATA ANALYSIS CONSOLE

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Group 64

TECHNICAL NOTE 1968-14

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LEXINGTON MASSACHUSETTS

ABSTRACT

A software system for a PDP-7 digital computer with a cathode ray tube display has been designed to process seismic data. The system permits quick visual inspection of digitized data and allows easy application of powerful programs which operate on the digitized data or on the results of previously used programs. Some operations which can be performed are: epicenter location, beamforming, magnitude, complexity and spectral ratio computation, filtering, autocorrelation, Fourier transformation, sonogram generation and automatic event detection. A human operator is in the processing loop, inspecting the output at each step before applying the next. This system has greatly increased the speed and efficiency of much of our seismic data processing.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

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I. GENERAL

There is a trend for data acquisition and other field systems to use digital magnetic tape as the recording medium in lieu of analog devices such as chart, film or analog tape recorders. This trend is likely to increase as cheaper and more reliable digital tape recorders become available and processing by digital computers becomes more popular. Digital tape recording has some large advantages over most analog recordings, viz. multichannel capability, precise timing, increased dynamic range, improved accuracy,* and compatibility with digital computer input devices. Experimenters are reluctant to use digital systems, however, because of the increased cost and complexity concommitant with these systems and also because it is difficult to visually examine the data. This paper describes a system which not only circumvents the latter difficulty, but makes standard data processing schemes that require the full power of a digital computer easy to use, apply, and interpret.

The Lincoln Data Analysis Console is a computer-oriented system which is designed to analyze seismic data from the Large Aperture Seismic Array (LASA).[1] (It can be used to analyze any data which has been digitized onto magnetic tape in any one of the several LASA formats.[2]) This system is designed to do many of the standard data processing tasks more efficiently and accurately, and yet be quicker and easier to

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* Off-the-shelf digital systems claim over 80 db dynamic range with 0.01% accuracy, while it is difficult to get more than 60 db and 0.1%, respectively, from analog recordings. It is interesting to note that the dynamic range and accuracy of digital systems is not limited by the recording method per se, but by the analog-to-digital converting processes.

use than a "batch processing" computer of the type that is found in most modern data centers. The system uses a cathode ray tube to display the input data or the computer output quickly and in an easily interpretable manner to a human data analyst who can alter the data or give new commands to the computer via a fiber optics light pen, adjustment knobs, or a teletypewriter keyboard (see Fig. 1).

This man-machine system puts a man in the feedback loop to do pattern recognition and to make decisions based on his experience as a trained seismologist or geophysicist, and to do other tasks that are very difficult for a modern electronic computer. The computer is in the loop at a place where it can function with an efficiency equal to or better than that of a human.

One of the difficulties of processing geophysical data in large computing centers arises from the large amounts of both input data that is required and output data that is produced. With data from a large seismic array such as the Montana LASA, the input might typically be a reel of magnetic tape and the physical output might be 25 feet of 32-channel chart recording, of which only 25 constants are useful output (which may be the input, along with the original data tape, to the next step in the processing). Each iteration or pass through the computing center takes time, generates a lot of superfluous data, and can introduce error in each two-way digital-to-analog and analog-to-digital conversion process (e.g. errors in reading the chart recorder and transcribing to punched cards).

The Lincoln Data Analysis Console is designed to eliminate these difficulties by presenting to the operator quickly and simply only that data which he desires to see. This data is presented in a quasi-analog manner, i.e., it appears analog to the eye and can be manipulated by analog devices (e.g. light pen and knobs), yet the full accuracy of the digital values is retained for computation because the data never leaves the computer. For example, the operator can easily scan the input data tape to insure it is not only good, but it is indeed the data he desires to have processed. Useless data is not put onto paper, but it is readily available for perusal if need be. Only after the data has been reduced, or after the operator decides he really wants it, is a permanent hard copy produced in the form of chart recordings, 'scope photographs, teletype copy or punched paper tape.

The system is organized so that the operator can have all the processing programs that have been written and debugged available literally at his fingertips. This ability to process the results of a prior processing without punching data cards and submitting for another pass through the computing center saves time. Typically, operations that take several days via other methods can be done in a few minutes on the analysis console.

II. THE MONITOR SYSTEM

The operation and control of the console are done by a master program which is called the MONITOR system. This program always resides in the computer core memory and controls the calling and execution of all the console system programs which are stored on magnetic tape or a drum as a program file. The MONITOR program always knows which programs have been used and hence which physical parameters have already been determined. The MONITOR saves all these parameters so that further processing will have access to them. Any processing that tries to use parameters which have not yet been determined will not be executed by the MONITOR until they have been determined. The MONITOR program is the only program that must be manually read into the computer. This is done once at the start. A self-protect feature makes it impossible to be destroyed by any of the software.

All commands to the MONITOR are input to the computer via the teletypewriter keyboard in a one-character mnemonic code. The MONITOR will fetch the proper program from the program file, transfer it into the core memory and execute it. All the programs are arranged so that they return to the MONITOR automatically. Control can be returned to the MONITOR prematurely by typing R (for return) on the keyboard.

III. THE DISPLAY SYSTEM

The console display system is the basic program from which most of the other programs are called. It is designed to make digitized seismograms accessible to a seismologist in a quasi analog manner to which he is accustomed. This program displays the seismograms (earth motion vs time) on the scope with six knobs controlling the parameters of the display.

The six knobs control the horizontal and vertical gain of the seismograms, the vertical separation between the seismograms, the horizontal and vertical position of the seismograms, and a clipping level. Figure 2 shows some typical examples.

The operator can use this program to scan the data visually and pick a portion of any seismogram for further processing by other programs. This picking is done by pointing the light pen at any waveform which causes it to be saved in a "reference buffer." The contents of this reference buffer will be displayed at the top of the screen with a vertical cursor appearing at the exact point in the waveform that was touched by the light pen. This "reference" trace is unaffected by most of the knobs. Thus one can, for example, move all the traces, one by one, alongside this reference by adroit manipulation of the horizontal and vertical position knobs to do visual alignment and correlation. This process is used to pick arrival times for the various traces to be used for beamforming and location (see below). By proper adjustments of the gains, this time picking can easily be done with a precision of one sample (50 milliseconds when using short-period data) as illustrated in Fig. 3.

IV. THE CONSOLE PROGRAMS

Some of the operations that can be done with the analysis console will be briefly described.* The system is designed so that additional programs can easily be added when they are written and checked out.

A. INITIALIZE

This is usually the first program that is called and executed. It reads the data tape and determines which of the several allowable formats the tape has been recorded in. (Each site may have its own tape format.) The program types out this information, along with the date and starting time of the data tape. The operator can select which data channels he wants to operate upon (there may be up to several hundred channels recorded on the data tapes) and what sampling interval should be used. The sampling can be changed by instructing the computer not to use every sample that was recorded, but to skip a fixed number of data samples from each channel. This program initializes all the other programs to use these pre-selected parameters.

B. LOCATION

If three or more arrival times are picked, either by the Display program or by manually typing them in, the best fitting plane wave that minimizes the r.m.s. error

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* A detailed description of all the programs is available from the author on request.

will be calculated. From this, the horizontal phase velocity and azimuth will be calculated. In addition, the relative arrival times when this plane wave would hit all 21 sites, along with the residuals from these times, is typed out. Provision is made for deleting times from any sites that may have large residuals and repeating the calculations. (If the data is from short-period seismometers, station corrections will have automatically been inserted in this calculation, and the distance from the center of LASA, the latitude and longitude of the epicenter will be computed. Also, G.M.T. time at which that portion of the seismogram corresponding to the reference cursor must have originated will be calculated, assuming a focal depth of 33 km.) Two constants giving the major and minor axes of the location uncertainty ellipse are also typed out. Provision is made for manually deleting the station corrections. Figure 4 shows the output for the event shown in Figs. 2 and 3.

C. BEAMFORMING

If one or more time picks are made via the Display program or the manual type-in program, the delay-and-sum beam will be formed and placed in the reference buffer as in Fig. 5. From here, it can be filtered (see below) or used as a reference to pick arrival times from weak events. Channels that have been deleted in the Locate program (above) will also be automatically deleted from the beam.

D. CONSTANTS

This program displays the reference waveform on the scope. Two points can be selected by the light pen and the G.M.T. time corresponding to each point will be displayed to the nearest 0.1 second. In addition, the time difference between the points and the amplitude difference in millimicrons corresponding to the two points picked (assuming normal calibration for the data) will be displayed. The magnitude based on these last two quantities will be typed out on request if the distance has already been computed. Provision is made for inputting the distance if it has not been computed. If the data is from a short-period instrument, the "Q" factors for a depth of 33 km are used. See Figure 6.

E. FILTERING

The data stored in the computer (21 seismograms, each 600 samples long) or the reference can be filtered. Currently, one has the choice of two filters which have been found useful in the past for short-period data.

1. Notch Filter
   This is a low distortion filter with two notches in the frequency response (at 0.2 and 0.3 Hz) to attenuate microseismic noise occurring around these frequencies. Zero frequency is attenuated about 10 db and frequencies higher than about 1 Hz pass through with little attenuation or phase shift.

2. Butterworth Filter
   This is a three-pole bandpass filter with 3 db points at 0.6 and 2.0 Hz. Both zero frequency and high frequencies (~30 db at 5.0 Hz) are attenuated, but some phase distortion occurs.

Figure 7 shows some examples of the use of these filters.

F. PLOT

This program plots all the waveform data stored in the computer on the Sanborn chart recorders so that hard copy can be obtained. This gives a much larger scaling than photographs of the 'scope can.

G. TRANSFORM

This program computes and displays the autocorrelation function of the reference waveform (512 data points), which has been modified as follows:

$$f_j^{MOD} = \begin{cases} 0 & j < A,\ j > B \\ f_j^{REF} & A \le j \le B \qquad j = 1,\ 512 \end{cases}$$

where A and B are set to any values via the light pen.

The finite Fourier transform of either the modified reference or of its autocorrelation function (both considered periodic with a period of 512 samples) can be computed. The autocorrelation function can be modified by an adjustable rectangular window. The periodogram of this transform is normalized and displayed (db <u>vs</u> frequency) and it can be output onto paper tape. Figure 8 shows some examples.

H. COMPLEXITY

This program computes and types out the complexity of the reference trace (beam or seismogram) starting at the cursor. The complexity is defined as follows:

$$C = \frac{\displaystyle\sum_{j = t_c + 5\ \mathrm{sec}}^{t_c + 35\ \mathrm{sec}} (f_j - \bar{f})}{\displaystyle\sum_{j = t_c}^{t_c + 5\ \mathrm{sec}} (f_j - \bar{f})}$$

where t_c is the time of the cursor that was set by the light pen, and

$$\bar{f} = \frac{1}{20} \sum_{j = t_c - 20\ \mathrm{sec}}^{t_c} f_j \ .$$

I. SONOGRAM

A sonogram is a display of signal intensity (represented by several different levels of brightness) as a function of frequency (vertically) and time (horizontally). Figure 9b shows the sonogram of the test calibrate signal of Fig. 9a.

This sonogram uses a bank of 50 constant bandwidth filters, each with a (sin x/x) type frequency response, with impulse response exactly 10 seconds in duration. The filters are spaced 0.1 Hz apart, and they cover a range of 0.1 to 5.0 Hz. The input to

these filters is the reference trace starting 1200 samples before the data displayed in the reference buffer and continuing for 3200 samples. The sonogram time scale, therefore, covers a range of 160 seconds if short-period data is used or over 2 hours if long-period data is used.

Each output of the 50 filters is full-wave-linear rectified to form the signal intensity,* and passed through two low-pass filters in cascade. The first is an energy summing "integrate and dump" filter. It sums the output of the rectifier for 20 samples, then resets itself to zero and repeats. The second filter takes these outputs, sampled just before the dump and performs "RC" type low-pass filtering. The 3 db cutoff of this latter filter is 0.11 Hz. The computer stores the output of this bank of 50 "RC" filters in a two-dimensional array of power vs frequency and time. The sonogram is simply the pseudo three-dimensional display of this two dimensional array.

If, for every time element in the sonogram array, the intensity at every frequency is summed, a one-dimensional "energy profile" array is formed. This program calculates and displays this energy profile as a series of 160 fine dots at the top of the display.

If, for every frequency element in the sonogram array, the intensity between two set times is summed, a one-dimensional "frequency spectrum" is formed. This program allows the two times to be manually set via the light pen. The spectrum is

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* Intensity rather than power is computed because it makes less stringest requirements on the dynamic range of the internal computer calculations.

displayed as a series of 50 coarsely spaced dots superimposed upon the energy profile. Both these latter displays are automatically normalized to use all the room on the scope available to them.

The spectral ratio[3,4] can easily be calculated by summing the proper elements in the sonogram array and taking their ratio. This is done and the result is output on the teletypewriter.

J. AUTOMATIC EVENT DETECTION

This program scans the data tape and types out the time of all teleseisms encountered. The actual mechanism by which teleseisms are distinguished from microseismic and other types of interference has been discussed elsewhere.[5,6] This operation takes place much faster than real time so that one can start with this program and quickly find all the events on the data tape, then analyze each separate event by using the programs described earlier.

K. CONVOLUTIONAL MATCHED FILTERING

This program cross correlates the reference trace with a matched filter that is especially designed to enhance the S/N of long-period dispersed surface waves.[7] The matched filter is a sinusoid with a linear frequency modulation (chirp). The matched filter has three parameters that can be input to the program via the teletypewriter. They are: the period at the start of the chirp; the period at the end of the chirp; and the

length of the chirp. The maximum allowable length of the chirp matched filter is 800 samples which corresponds to 160 to 1920 seconds depending on the sampling chosen in the Initialize program. Enough of the input reference will be convolved with this chirp to give 512 samples of filtered output, which will appear in the reference buffer. Figure 10 shows a typical example of this type of filtering.

ACKNOWLEDGEMENT

The programs described in this report are due to L. Fleck, R. Gay and L. Turek, and their help is gratefully acknowledged. Also, I should like to thank all those users, especially H. Briscoe, who have used this system and given valuable suggestions for improvements and additions. Finally, I wish to thank Mrs. L. Merikanto for without her repeated efforts this report would never have been written.

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7. J. Capon, R. J. Greenfield and R. T. Lacoss, "Long-Period Signal Processing Results for Large Aperture Seismic Array," M.I.T., Lincoln Laboratory Technical Note 1967-50, 15 November 1967, DDC 663429.

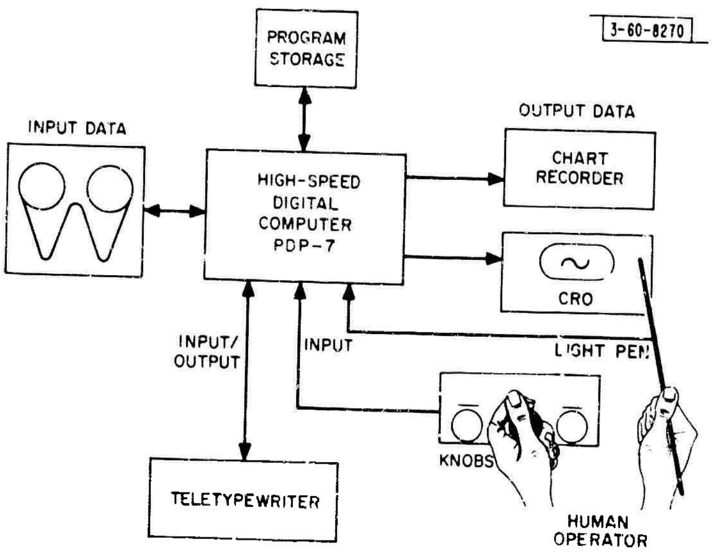

Fig. 1. The Lincoln Data Analysis Console.

-64-8810

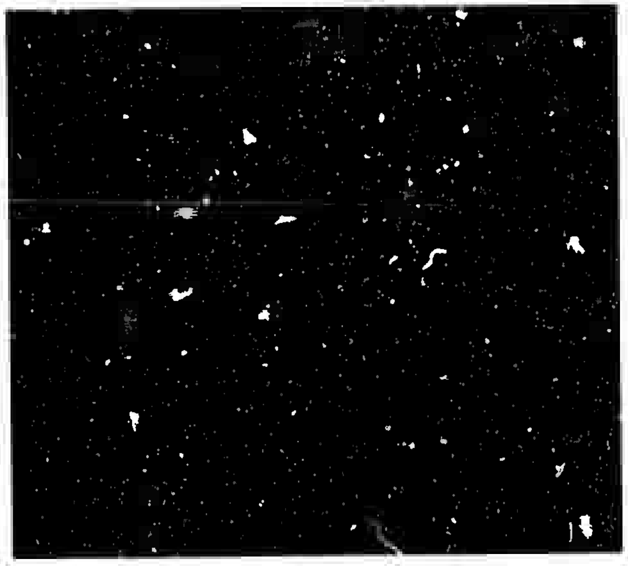

Fig. 2a. All 21 seismograms.

-64-8811

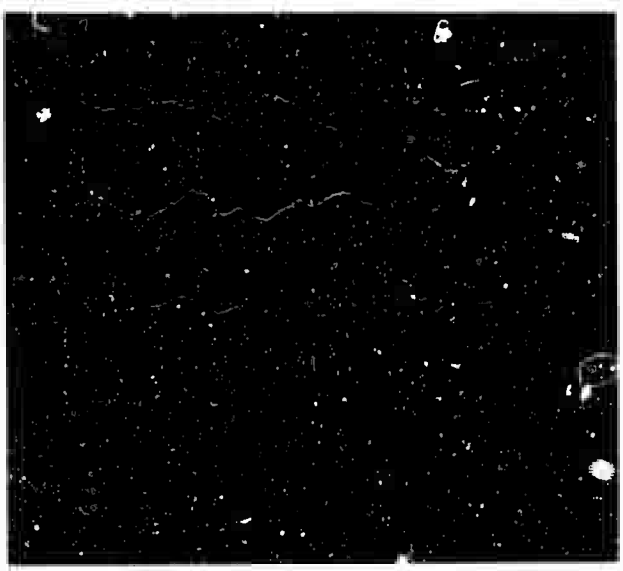

Fig. 2b. The top four seismograms with greater gain and separation.

-64-8812

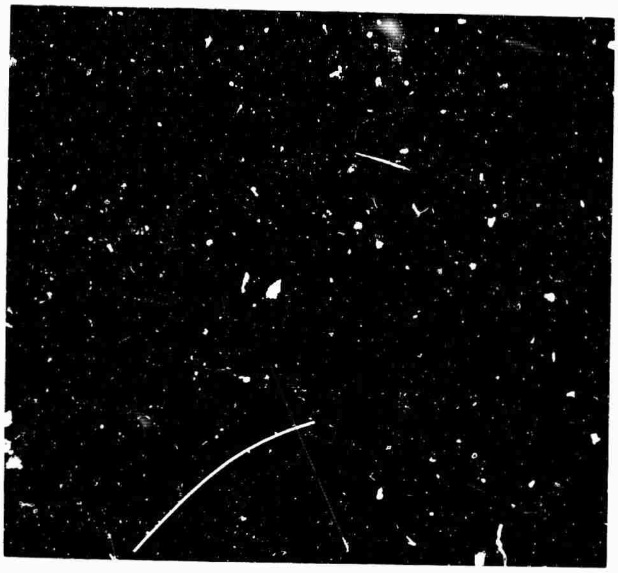

Fig. 3a. Seismogram No. 4 used as reference and aligned with No. 1.

-64-8813

Fig. 3b. Same except aligned with No. 2 and more gain.

-64-8814

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1/14           13    46    39

VBAR=  22.83  AZIMUTH= 294.44      WITH LHAT=      .085

EPICENTER WAS  19.05 N       147.67 E
  86.75 DEGREES FROM LASA
ORIGIN    13 33 57
LAMBDA(1)=   .1421 RAD/SEC         LAMBDA(2)=   .1211 RAD/SEC
SITE   ARRIVAL  RESIDUAL  MEASURED
 F1    10.034     -.032       .00
 F2    12.145      .058      1.70
 F3     7.081      .000     -3.15
 F4     4.671      .072     -5.55
 E1     7.848      .148     -2.14
 E2    11.273      .014      1.10
 E3     9.043     -.086     -1.40
 E4     6.037     -.017     -4.00
 D1     9.008     -.112     -1.10
 D2     9.322      .072      -.95
 D3     7.792     -.095     -2.40
 D4     7.302     -.106     -2.85
 C1     8.286     -.145     -1.85
 C2     8.980     -.055     -1.10
 C3     8.448      .174     -1.60
 C4     7.745     -.017     -2.30
 B1     8.571     -.054     -1.50
 B2     8.591      .060     -1.40
 B3     8.072      .074     -1.90
 B4     8.078     -.031     -2.00
 A0     8.302      .078     -1.60
```

Fig. 4. Output of locate program.

-64-8815

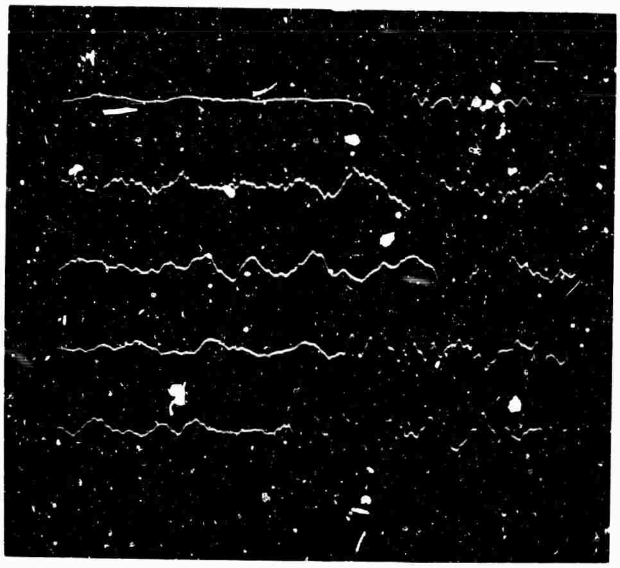

Fig. 5. Beam formed from all 21 seismograms at top. Notice improved S/N.

-64-8816

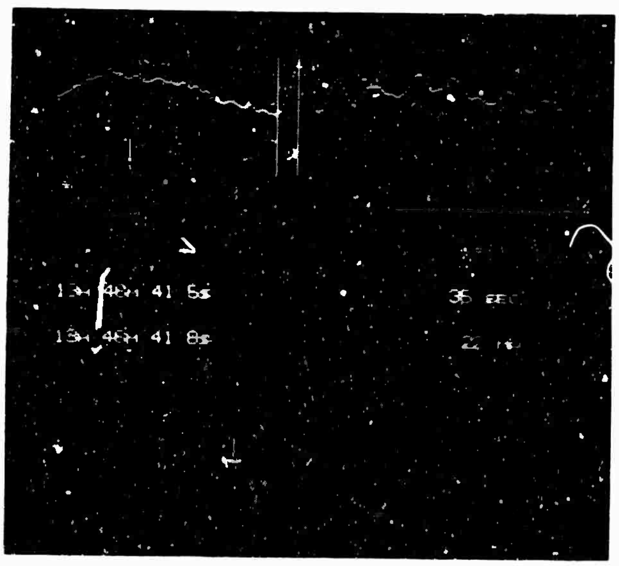

Fig. 6. Some constants for top seismogram of Fig. 2. Note that the vertical lines can be moved at will with the light pen. The teletypewriter typed MAG=5.2.

-64-8817

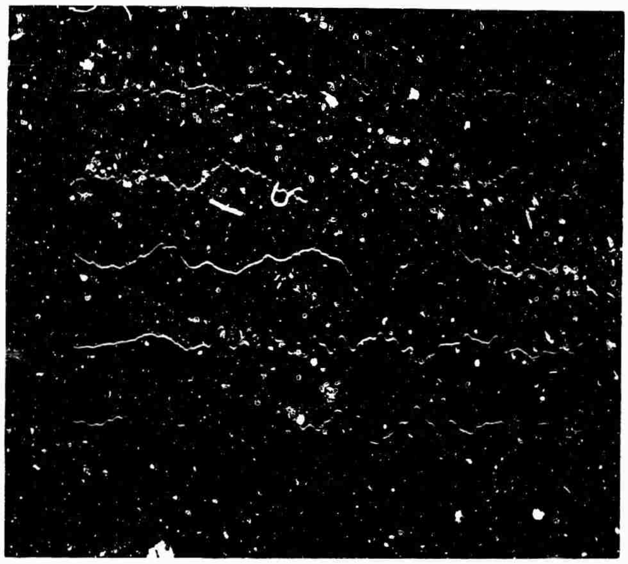

Fig. 7a. Top trace is notch filtered. Second trace: raw data.

-64-8818

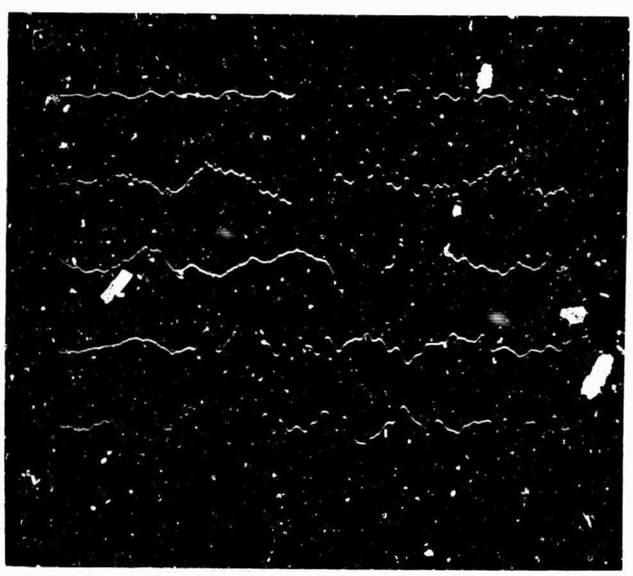

Fig. 7b. Top trace is Butterworth filtered. Second trace: raw data.

-64-8819

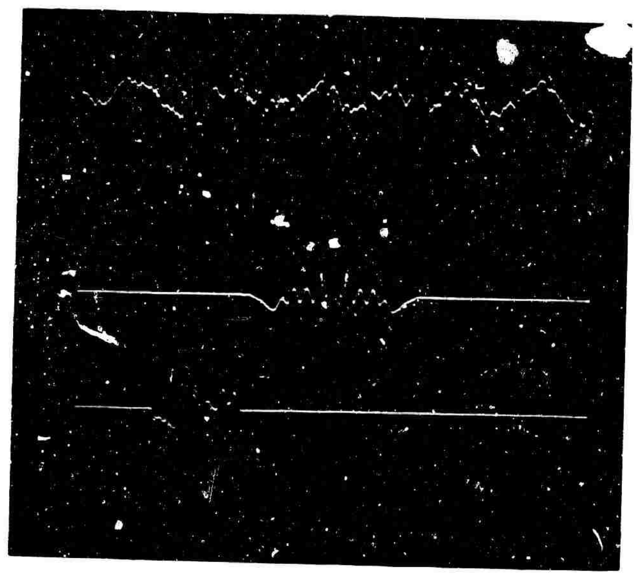

Fig. 8a. Top trace is input data. At the bottom, a certain portion is selected with the light pen. The middle trace is the autocorrelation function of the bottom trace.

-64-8820

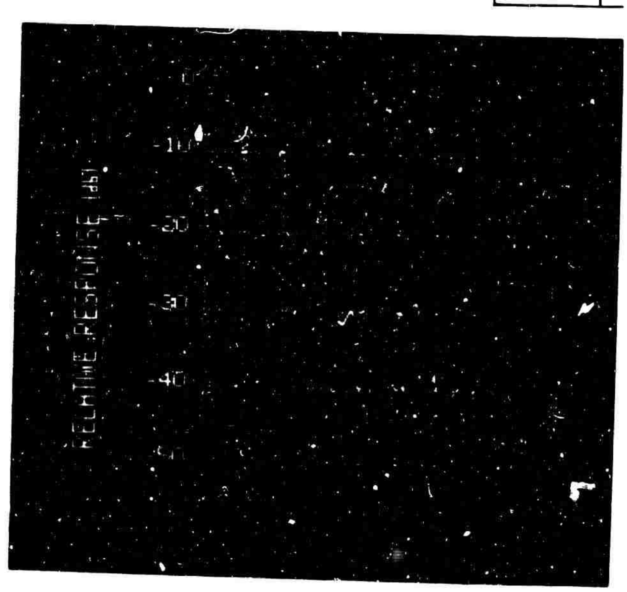

Fig. 8b. Periodogram of the bottom trace of Fig. 8a.

-64-8821

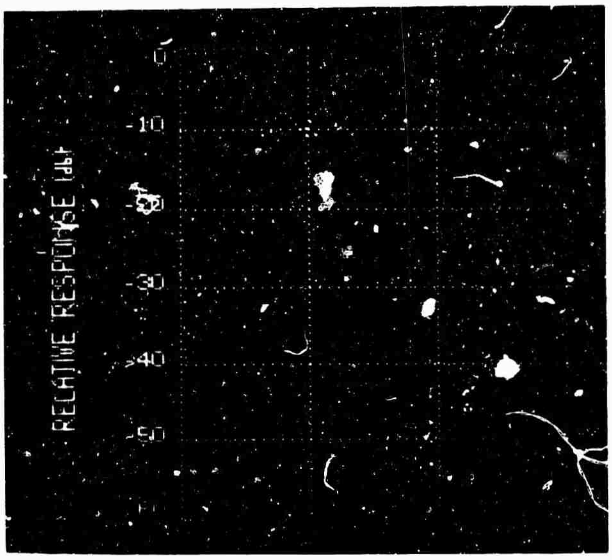

Fig. 8c. Same as Fig. 8b showing the first three Hz expanded.

-64-8822

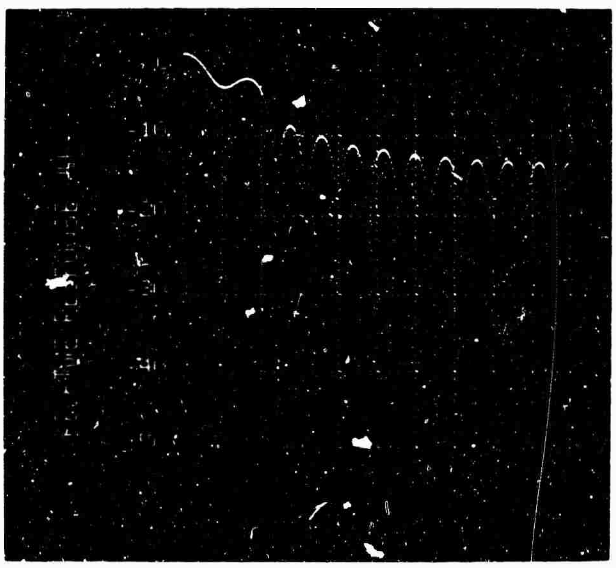

Fig. 8d. Periodogram of the autocorrelation function of Fig. 8a after it has been modified by a rectangular window (vertical lines in center portion of Fig. 8a).

-64-8823

Fig. 9a. Calibrate signals on various channels.

-64-8824

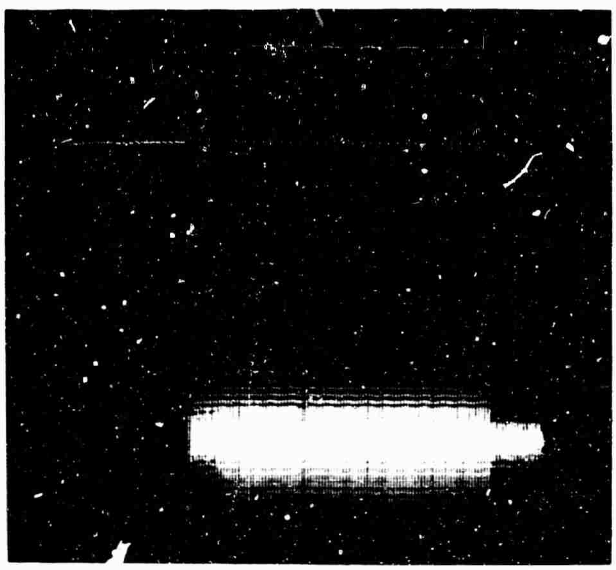

Fig. 9b. Sonogram of top trace of Fig. 9a. Note energy profile (fine dotted line) and spectrum (coarse dotted line) at the top. Note slight third harmonic distortion inadvertently present in the calibrate signal.

-64-8844

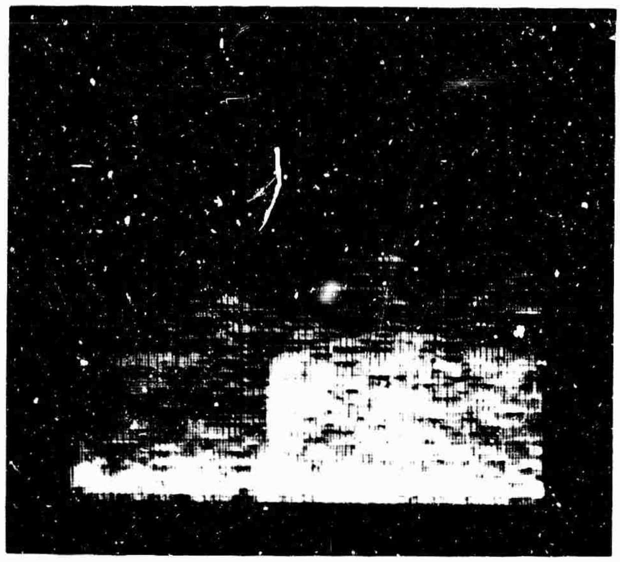

Fig. 9c. Sonogram of top trace of Fig. 2b. Teletypewriter typed SPECTRAL RATIO = 0.647.

-64-8825

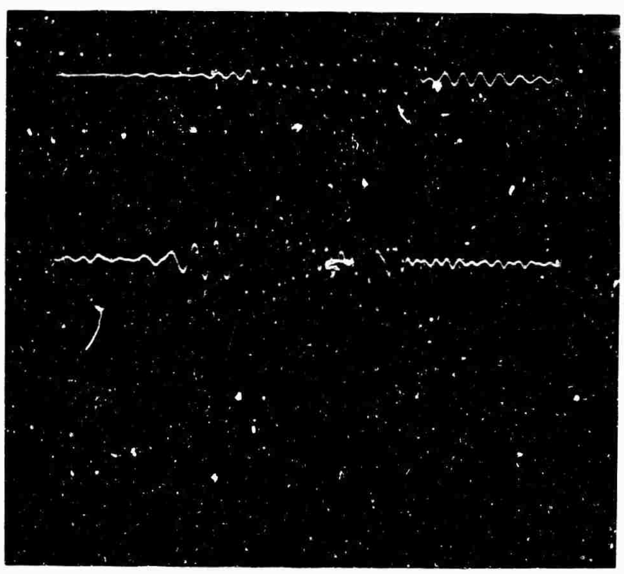

Fig. 10. The top trace is the result of convolving the Rayleigh wave shown in the bottom trace with a chirp filter 400 seconds long with a starting period of 40 seconds, and an ending period of 16 seconds. The sampling interval is 1.2 seconds and the horizontal scale is 10.24 minutes.

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13. ABSTRACT

A software system for a PDP-7 digital computer with a cathode ray tube display has been designed to process seismic data. The system permits quick visual inspection of digitized data and allows easy application of powerful programs which operate on the digitized data or on the results of previously used programs. Some operations which can be performed are: epicenter location, beamforming, magnitude, complexity and spectral ratio computation, filtering autocorrelation, Fourier transformation, sonogram generation and automatic event detection. A human operator is in the processing loop, inspecting the output at each step before applying the next. This system has greatly increased the speed and efficiency of much of our seismic data processing.

14. KEY WORDS

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digital systems	seismic data analysis